Ecological Modelling 268 (2013) 48–54

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Application of Bayesian networks for sustainability assessment in catchment modeling and management (Case study: The Hablehrood river catchment)

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ARTICLE INFO

Article history:
Received 24 February 2013
Received in revised form 6 August 2013
Accepted 6 August 2013
Available online 8 September 2013

Keywords:
Bayesian network
Sustainability assessment
Integrated catchment management
Vegetation management
Decision support
Iran

ABSTRACT

Catchment management is a process which increases the sustainable development and management of all catchment resources in order to maximize the balance among socioeconomic welfare and the sustainability of vital ecosystems. The increase of anthropogenic activities within river catchments causes degradation and serious problems for stakeholders and managers, particularly in arid and semi-arid regions. Although there are many techniques for solving these problems, it is not easy for catchment managers to apply them. An integrated Bayesian network model framework was applied to evaluate the sustainability of a semi-arid river catchment located in the Iranian Central Plateau river basin encompassing 32.6 km^2 area on the Hablehrood river catchment, located in the northern part of the Iranian Central Plateau river basin. The research illustrated the assessment of the relevant management problems, the model framework, and the techniques applied to extract input data. Results for the study area implementation and a suggestion for management are described and discussed.

1. Introduction

Catchment management tries to solve catchment issues based on sustainable development. Among these issues, degradation of water quality has become the critical limit of catchment development in many catchments of the world including the arid and semi-arid catchments of the Iranian Central Plateau river basin. Hence, one of the main objectives of catchment management is to find solutions in order to protect and restore water quality. It is necessary to have the stakeholders' participation to obtain an integrated catchment management plan that includes water quality and quantity objectives. Combining the needs and objectives of decision-makers and stakeholders is the main advantage of using integrated catchment management.

Generally, the most widely discussed themes in catchment modeling and management include uncertainty. The past decades have shown an increasingly significant interest in probabilistic assessment, risk analysis, and related subjects and methods (Varis, 1997). Probabilistic assessment and risk analysis methods are widely used.

Recently, the utilization of graphical models, such as Bayesian networks (BNs), has grown rapidly in natural resources modeling and management under uncertainty and integrated water and catchment management.

Many authors have used BNs to better understand and model many complicated problems in such fields as medicine and artificial intelligence (Charniak, 1991; Pearl, 1988; Heckerman et al., 1995; Jensen, 1996). BNs have been applied to various ecological problems (Kuikka et al., 1999; Borsuk et al., 2002; Little et al., 2004; Prato, 2005; McCann et al., 2007; Pollino et al., 2007; Aalders, 2008; Bashari et al., 2009; Liedloff et al., 2009; Mesbah et al., 2009; Reckhow, 2010). Applications of BNs in water resources include groundwater management (Martin de Santa Olalla et al., 2007; Henriksen et al., 2007; Farmani et al., 2009; Malekmohammadi et al., 2009), irrigation and farming system modeling (Batchelor and Cain, 1999), and by Varis and Kuikka (1997) to study the effect of climate change on surface waters. BNs were applied by Borsuk et al. (2001, 2004), Hamilton et al. (2007), Johnson et al. (2009) and Alameddine et al. (2010) to investigate the eutrophication of various water bodies. Some studies reviewed applications of BNs in integrated natural resources management and catchment

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http://dx.doi.org/10.1016/j.ecolmodel.2013.08.003

modeling (Ames et al., 2005; Bromley et al., 2005; Sadoddin et al., 2005; Khadam and Kaluarachchi, 2006; Said, 2006; Zobrist and Reichert, 2006; Castelletti and Soncini-Sessa, 2007a; Davies, 2007; Dorner et al., 2007; Ticehurst et al., 2007; Barton et al., 2008; Fox and Papanicolaou, 2008; Kragt, 2009; Kragt et al., 2009; Stewart-Koster et al., 2010; Merritt et al., 2010; Holzkämper et al., 2012). The objective of this paper was to apply Bayesian network modeling to assess the sustainability of social, economic, and ecological conditions within a semi-arid catchment. In particular, we present how management action costs can be coupled with these conceptual models to recognize the most cost-effective management action and select the best management plans to improve river water quality using Bayesian networks.

1.1. Bayesian networks

BNs (also called belief networks or causal probabilistic networks) include a set of nodes (variables) and causal links. BNs are used to conceptualize and simulate a system which consists of uncertain consequences through incomplete understanding or insufficient knowledge of a system (Pearl, 1988). BNs consist of a graphical model and a fundamental probabilistic structure; the graphical model represents the most significant variables in the system and causal links between the nodes. The causal links between nodes are explained using conditional probability tables (CPTs). The empirical data, various models, and expert technical inputs (when measured data are not accessible) are information sources to produce CPTs (Pearl, 1988; Jensen, 1996). There are a number of benefits with BNs such as integrating different types of variables and data within a single framework, describing uncertainty, and the ability to be updated when new information and knowledge become available (Castelletti and Soncini-Sessa, 2007b; Cinar and Kayakutlu, 2010). They are also applicable as a tool to assist decision-making in natural resources management, where issues are complicated and data are insufficient and uncertain. The framework of Bayesian networks and their applications in participatory modeling can be found in other studies (Borsuk et al., 2004; Castelletti and Soncini-Sessa, 2007b; Jensen, 2001).

We used BNs because their applications are comparable to other integrative models as an effective tool to integrate social, economic, physical, and ecological variables. In this paper, we present a case study of the application of BNs in catchment modeling and management.

2. Materials and methods

2.1. Study area

The Hablehrood river catchment (HRC) (35° 13′ to 35° 57′ N, 51° 39′ to 53° 8′ E) is located in northwestern Semnan and northeastern Tehran provinces, on the northern part of the Iranian Central Plateau river basin, with a total surface area of approximately 32.6 km^2 (Fig. 1). The mean annual precipitation and air temperature of this river catchment are 318 mm and 7.8 °C, respectively. The Hablehrood river, which originates from the Alborz Mountains, flows north to south and is bound by mountains except at its outlet (at the location of Bonkooh hydrometric station), where it empties into the Garmsar Plain. The catchment area is dominated by degraded rangelands; intense salinity outbreaks occur in the southern parts of the catchment. This maximum salt load is observed at the Bonkooh hydrometric station. The Hablehrood river supplies water for the municipal consumption of the city of Garmsar which has a population of over 84,000, for industry, and for farmlands on the Garmsar Plain (about 5.2 km^2).

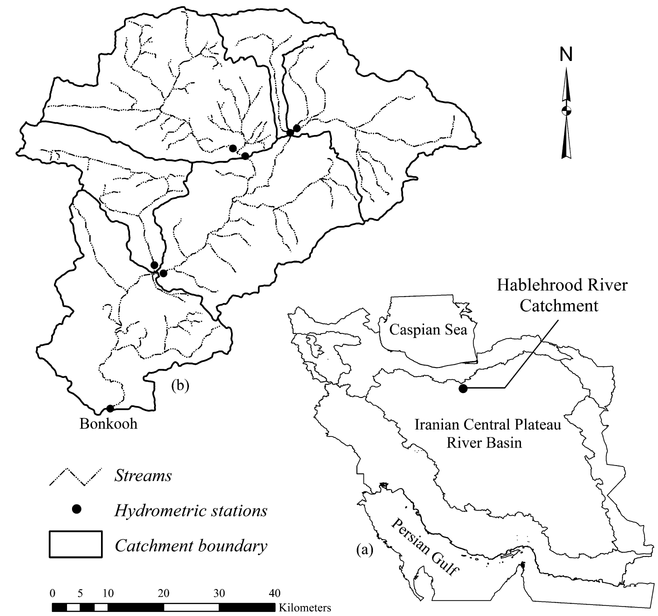

Fig. 1. (a) Geographical location of the study area in Iranian Central Plateau river basin; (b) map of the Hablehrood river catchment.

The Hablehrood river catchment has significant natural, social, and economic value, such as medicinal plant species like *Ferula* sp., natural rangelands, water resources for the city of Garmsar, and irrigation. The most effective factors on the Hablehrood river catchment's sustainability are overgrazing, intensive farming on the Garmsar Plain, and urban development due to population growth in the city of Garmsar. Managers need the appropriate tools to analyze the consequences of management actions in order to balance human activities with environmental issues and improve water quality. BNs were chosen as a practical approach to analyze these interactions.

2.2. Model development process

A Bayesian decision network was developed to analyze the consequences of suggested management plans on the sustainability of the Hablehrood river catchment. In the first step of the model construction, we reviewed previous implemented management actions, studies, and other scientific articles to better understanding the limitations, problems, and the needs of stakeholders and communities involved (Ames et al., 2005; Carmona et al., 2009; Sadoddin et al., 2005; Schwilch et al., 2012; Ticehurst et al., 2007; WNRMO, 1998). An initial review assisted in determining a preliminary BN structure and possible management actions.

2.3. Model structure description

The preliminary BN framework was presented and discussed with local community leaders and the Watershed and Natural Resources Management Office (WNRMO), which is responsible for the sustainability of the Hablehrood river catchment. This helped to refine and improve the preliminary BN framework. A simplified version of the improved BN model is shown in Fig. 2. For example, river water quality is shown as a single node in Fig. 2, but the original model structure contains three separate nodes, including; Total Dissolved Solids (TDS), Electrical Conductivity (EC) and Sodium Absorption Ratio (SAR). The current model includes 19 nodes and 29 links. The models' nodes and their states are described in Tables 1 and 2.

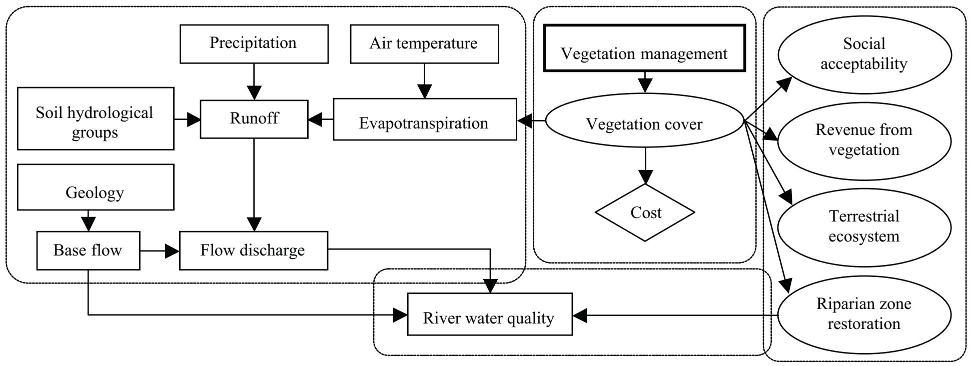

Fig. 2. Bayesian network for the improvement of water quality in the Hablehrood river catchment.

Table 1
Variables for water quality management in HRC Bayesian network.

Variables	Description
Precipitation	Daily rainfall (mm)
Air temperature	Daily rate of air temperature (°C)
Evapotranspiration	Monthly amount of real evapotranspiration (mm)
Runoff	Runoff rate (mm)
Soil hydrological groups	Extent of each group (%)
Geology	Extent of each permeability rate (%)
Baseflow	Daily measured rate of base flow(m^3/s)
Flow discharge in stream	Daily measured rate of flow discharge (m^3/s)
Hablehrood river water quality	TDS: daily TDS rate at Bonkooh station (mg/lit)
Hablehrood river water quality	EC: daily EC rate at Bonkooh station (μm/cm)
Hablehrood river water quality	SAR: daily SAR rate at Bonkooh station
Vegetation cover	Extent of each types of vegetation cover (%)
Social acceptability	Public agreement or disagreement about recommended management actions (%)
Riparian zone restoration	Length of riparian zone (km)
Terrestrial ecosystem condition	Rangeland changes in the area and quality (%)
Revenue from vegetation management	Forage production income (kg/ha)
Cost of vegetation management	The total cost of vegetation restoration within the HRC

Table 2
Variables and their states in HRC Bayesian network.

Variables	States
Precipitation	<5.5Ymm, >5.5Ymm
Air temperature	<10.5°C, > 10.5°C
Evapotranspiration	<23.25Ymm, >23.25Ymm
Runoff	Yes, No
Soil hydrological groups	A, B, C, D
Permeability	Weak, medium, good
Base flow	<4.3 m^3/s, >4.3 m^3/s
Flow discharge in stream	<8.1 m^3/s, >8.1 m^3/s
Hablehrood river water quality (TDS)	<1000Ymg/l, 1000–3000Ymg/l, >3000Ymg/l
Hablehrood river water quality (EC)	<750 μm/cm, 750–2250 μm/cm, 2250 μm/cm
Hablehrood river water quality (SAR)	<10, 10–18, >18
Vegetation cover	Decrease, constant, increase
Social acceptability	Not acceptable, slightly acceptable, moderately acceptable, highly acceptable
Riparian zone	Weak, medium, good
Terrestrial ecosystem condition	Weak, medium, good
Revenue from vegetation management	Decrease, constant, increase
Cost of vegetation management	No change, 0–50% increase, 50–100% increase, >100% increase

2.4. Scenario development

The management actions (decision nodes) are shown in Table 3, which indicates a summary of the effective work that can be studied in the Hablehrood river catchment BN. Land management units were determined to simulate the potential spatial land cover patterns with a combination of geomorphology, geology, elevation, slope, and topographic maps (Ahmadi, 2005). The base case

Table 3
Management actions for decision node in the HRC Bayesian network.

Number	Management action	Implementation area
1	Rangeland improvement	Entire catchment is potentially suitable, not in the potential riparian areas
2	Lucerne adapting	Only in areas currently under dry farm
3	Riparian restoration	Only in potential riparian areas
4	Tree plantation	Only in areas currently under native tree

scenario includes the actions that do not show changes in the current situation. In addition to the base case option, there are 16 scenarios ($2^4 - 1$) of various combinations of management actions.

2.5. Conditional probability tables

Conditional probability tables of the nodes assist model updating (based on Bayes' theorem) (Castelletti and Soncini-Sessa, 2007b) and demonstrate the sensitivity of the reaction variable to management actions. Populating conditional probability tables is applied to quantify the network. In Bayesian networks, CPTs can be generated using different information sources consisting of measured data, model simulation, expert judgment, and economic investigation or stakeholders' surveys (Ames et al., 2005).

The Hablehrood river catchment CPTs were specified using a combination of expert judgments or data analysis, simulation model results, and literature review. Quantitative data were generated using model simulation and data analysis, but qualitative inputs were generated by expert opinions and literature reviews (Ames et al., 2005; Kragt, 2009; Kragt et al., 2009; Sadoddin et al., 2005; Said, 2006; Ticehurst et al., 2007; WNRMO, 1998). Data analysis was used to specify the input values of probabilities such as rainfall events, and the model was run using all probable states of the input values. The CPTs of the model outputs were specified using the joint probabilities. In other cases, the experts' judgments and stakeholders' opinions, who participated in the preliminary BN development were used to generate and review CPTs. Lack of proper data and difficulty in monitoring or describing some characteristics are the main abstractions for generating the conditional probability tables of the additional variables in the Hablehrood river catchment. Some measured data sets were available (such as rainfall), but it was difficult to access other appropriate observation data in the time available for model development. Economic analyses, experts' judgments, and stakeholders' surveys were the sources of practical information for the determination of the prior conditional distribution (Ames et al., 2005; Kragt, 2009; WNRMO, 1998).

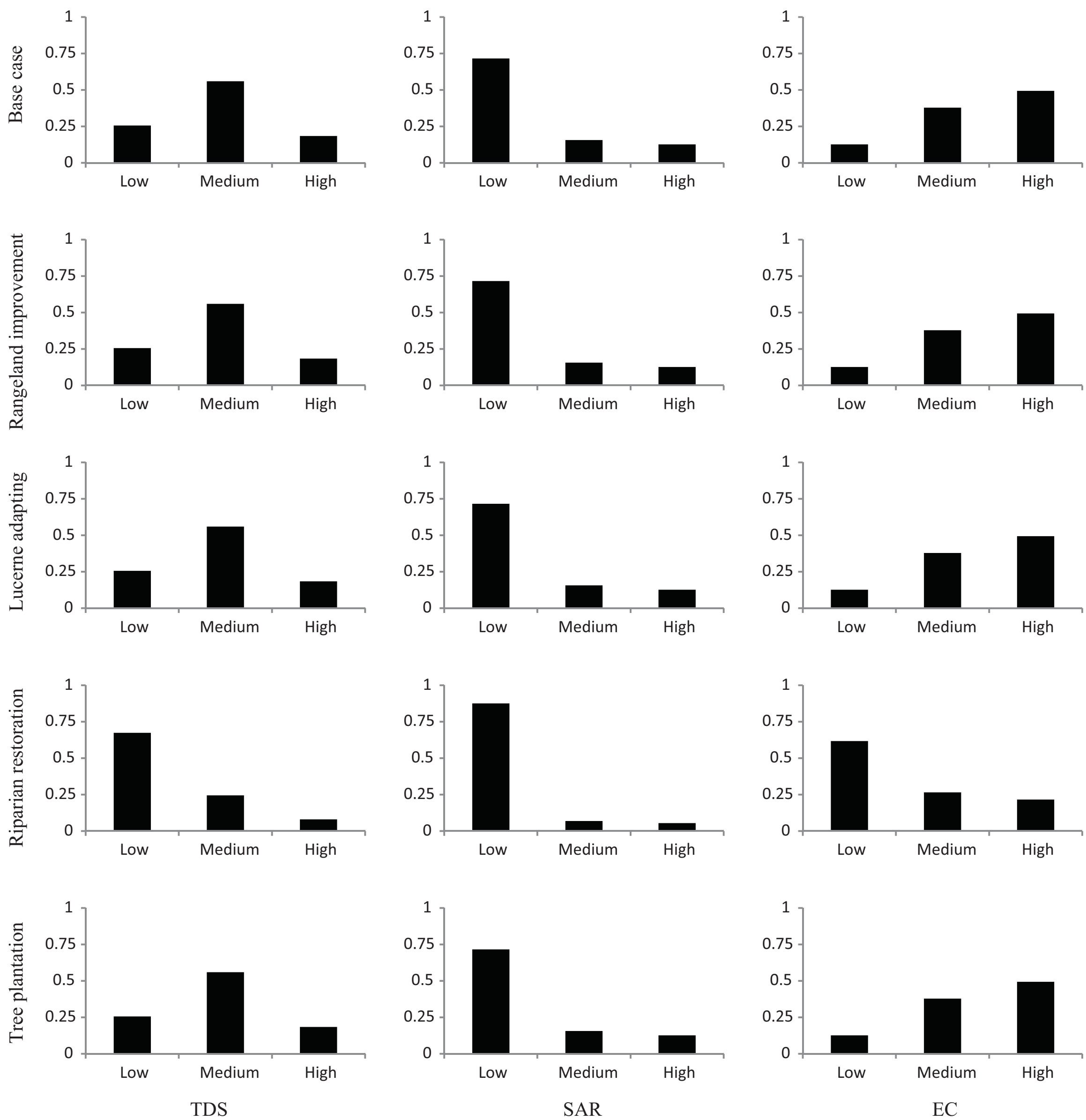

Fig. 3. Probability values of the water quality nodes, including total dissolved solids (TDS), electrical conductivity (EC) and sodium absorption ratio (SAR) for the given management actions.

Table 4
River water quality CPT at the Bonkooh station.

Action	Weak	Medium	Good
Base case	76.6	21.7	1.7
Rangeland improvement	76.5	21.8	1.7
Lucerne adapting	76.6	21.7	1.7
Riparian restoration	44.4	13.7	41.9
Tree plantation	76.6	21.7	1.7

2.6. Model validation and verification

A testing process is essential for verifying and validating results of the model, but it cannot be performed for the BN as a whole by analysis. Because of the BNs integrative nature, similar types of data for validating the whole process are not available. The model is developed to consider the next effects of management actions. Obviously, before the consequences of such management actions have been observed, these data and information cannot exist for validation. Hence, existing data including measured data (rainfall, air temperature, river water quality, permeability, baseflow, flow discharge in stream, soil hydrological groups, and vegetation cover), simulation model results (runoff and evapotranspiration), economic analyses, experts' judgments, and stakeholders' surveys are used for model validation and input data for each node at current situations. Validation of the whole process was carried out with the local experts and the group of stakeholders during meetings to control whether current model consequences are acceptable.

2.7. Software

BNs based models can be built using several accessible commercial software packages. Analytica (Lumina, 2004); Netica (Norsys, 2005); Hugin (Hugin Expert A/S, 2004); and GeNie (DSL, 2005) are the most famous software packages for BN. In this study, the BN was developed using the software package of Netica (Norsys, 2008). It applies the well-known Bayes' theorem to estimate the conditional probability of a variable conditioned to a prior one by the propagation of the probability. There are many practical utilizations for Netica, such as the ability to develop, learn, alter, change, and store nets and respond to questions or determine better solutions (Norsys, 2008) Moreover, the comprehensive, flexible, and user-friendly graphical user interface is its advantage (Uusitalo, 2007).

3. Results and discussion

BNs as practical decision-making tools support an evaluation of the relative changes in outcome probabilities associated with management actions. To assess the consequences of catchment management actions on the selected nodes, a change in the output CPT is compared to the current condition (base case). One of the useful capabilities of Netica software for model assessment is the observation of CPTs within the BN.

The results showed that implementing riparian zone restoration action and relative scenarios were the most effective among all scenarios and would change the current probabilities of the water quality at Bonkooh Hydrometric Station. Table 4 shows that riparian zone restoration management action would decrease the probabilities of water quality changes, and the likelihood of water quality is acceptable at 41.9. The output CPTs, indicated as bar charts for water quality nodes, are shown in Fig. 3.

Investigations showed that the probability changes for water quality were similar among scenarios relative to riparian zone restoration, if riparian zone restoration action is combined with other management actions. Thus, the impacts on water quality from the combined riparian zone restoration and other management actions are the same as those from riparian zone restoration alone. Furthermore, implementing rangelands improvement, Lucerne adapting, and tree plantation management actions and their relative scenarios had no impact on the current probabilities of water quality, implying that riparian zone restoration action would be the best conservation plan. Compared to other management actions, riparian zone restoration area covers less than 3% of the study area as it is located at the Bonkooh sub-catchment where it delivers the main salt load to the river. The importance of riparian zone restoration is undeniable, because most of the vegetation within the riparian zone along the Bonkooh sub-catchment has been eliminated by grazing and agriculture activities. Most of the saltbush plant communities on the riparian zone have been encroached upon to provide for agricultural practices or have been significantly changed by grazing (WNRMO, 1998). Droughts lasting 10 years impacted agriculture productions; consequently these areas are now bare of vegetation. As demonstrated by other researchers (e.g. Abernethy and Rutherfurd, 1999; Johnson and Buffler, 2008; Lovett and Price, 2007; Makkeasorn et al., 2009), the removal of deep-rooted vegetation plays a critical role in improving water quality.

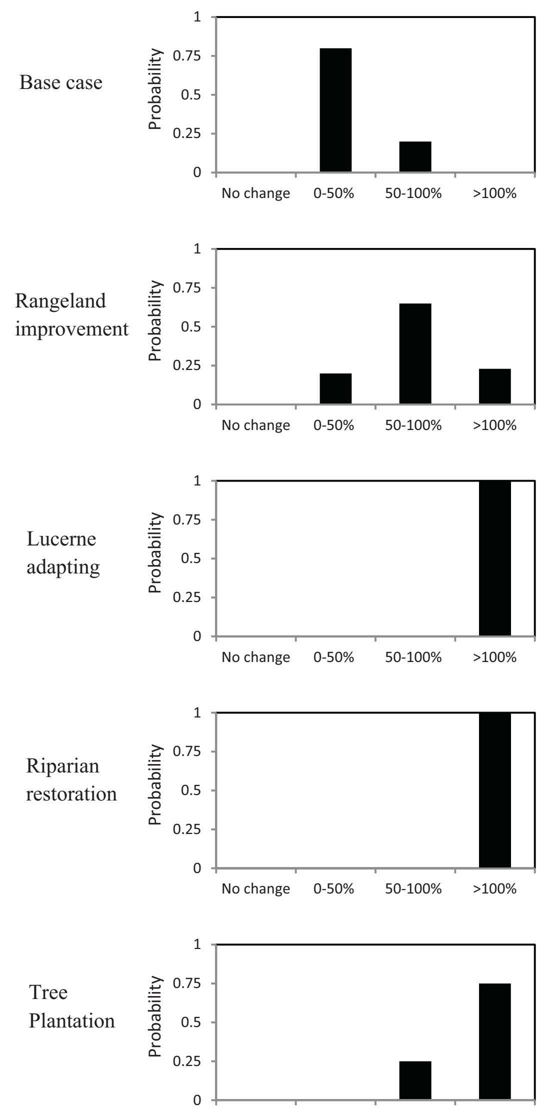

Fig. 4. Probability values of the total costs for the given management actions.

This is not to say that other management actions, especially rangelands improvement which covers about 90% of catchment and 43% of Bonkooh sub-catchment area, have no impact on water quality. The current model structure does not create a direct impact on the water quality in the study area.

All management actions reflect a rise in maintenance and performance costs to Natural Resources and Watershed Office. The best case management action indicates riparian zone restoration as the best management practice with the minimum total costs (Fig. 4). The arid and semi-arid catchments of the Iranian Central Plateau river basin, which covers 60% and 75% of the country's area and population, respectively, are the systems which strongly involve anthropogenic activities. They need effective management in order to obtain their sustainable development. Hence, managers need to assess the environmental, social and economic impacts of different management scenarios. There are not many methods to aid integrated management and scenario analysis. BNs, as modeling techniques, are useful tools in scenario creation and the analysis of complex planning and management in catchment issues. This study aims to develop a Bayesian network to represent the Hablehrood river catchment system as well as our knowledge about that system as a whole. Four management actions and 16 relative scenarios have been tested using Bayesian network modeling.

4. Conclusions

Catchment managers face a number of management problems (such as water quality degradation) that involve complex environmental and socio-economic systems and need integrated modeling. A major difficulty in integrated modeling research is the need to incorporate knowledge from various disciplines into a logically consistent framework. Moreover, the dynamics of dryland ecosystems are complex and involved in processes acting at different scales (temporal and spatial) (D'Odorico and Porporato, 2006). Many environmental and socio-economic processes, such as the hydrological dynamics of dryland rivers, are not yet well-understood and are subject to uncertainty. Applying a deterministic model that depends on measured and quantitative data will not be suitable when there is limited knowledge and/or information about a system.

BNs are useful and effective techniques for demonstrating experts' knowledge of an ecosystem, assessing potential results of alternative management actions, and communicating with nonexperts about selecting natural resource management options. They have a number of advantages like integrating frameworks such as providing the possibility of combining different types of data, representing uncertainty, and being able to update the model when new knowledge and data are available. They are able to represent complicated systems as a whole and do not need to illustrate all the processes in a system (Borsuk et al., 2004). The associated uncertainty of a system can be indicated using CPTs (Castelletti and Soncini-Sessa, 2007b), and it may lead to system errors and also our knowledge gaps. The managers are required to explicitly recognize the risks associated with various management actions in decision-making modeling. BNs can help by determining the most important variables that have a major influence on results but understood the least and by supporting the structuring and designing of adaptive-management trails to evaluate responses to management actions (McCann et al., 2007). They are also able to estimate the expected utilities and a decision node whose state is inherently computed to maximize the expected utility. BNs can be applied to integrate new research outcomes with current knowledge to solve catchment issues and select the best management actions.

The BN model applied in this study indicated that, in order to solve the problems of water quality degradation and effective catchment management, the participation of all involved groups is needed. It also combines various data into a single model framework. It is able to address what ecological processes are involved, which ones have the greatest influence on consequences and also show the consequences of different management scenarios as well as the uncertainty-associated system. Developed BNs also have the potential to update the model structure and CPTs when new data and knowledge become available. This study is the first effort to integrate catchment management and scenario analysis to obtain sustainable development and improve water quality in the arid and semi-arid catchments located in the Iranian Central Plateau river basin. Catchment decision-makers emphasized rangeland restoration and engineering management options for solving water quality degradation in the study area, but this research showed how, in a dryland ecosystem, riparian vegetation less than 3% of the total area is more important than upland and rangeland vegetation. It also showed the most effective management action in improving river water quality and the importance and key role of riparian vegetation in dryland rivers. It assists managers in making better decisions and choosing more effective management actions for all similar catchments.

Acknowledgements

Support for this research provided by the University of Tehran is greatly appreciated. The authors wish to acknowledge the Forests, Rangelands and Watershed Management Organization for preparing some data of the project. Also, the authors would like to thank E. Shahriari, L. Rafati, and S.M. Razavi for their assistance with preparation of the article. We are very grateful to B. Fath and two anonymous reviewers for many valuable comments on the manuscript.

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